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VOLTAGE-PROGRAMED CONTROL OF TURBOALTERNATOR LOAD

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16. Abstract

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SUMMARY

A power source and load-control concept was designed and tested for use with a Brayton cycle turboalternator. The concept involves full rectification of the alternator output, forming a dc bus which provides power that adjusts to a range of loads while controlling alternator speed and isolating load-switching transients. The system was found to be highly stable and efficient, and it allows a simple method of providing overcurrent and fault protection. The concept is also applicable to power-generating sources other than the Brayton cycle.

INTRODUCTION

Studies of long-term manned missions such as Manned Orbital Research Laboratory and Space Station/Space Base have identified electrical power requirements ranging from 10 to 100 kW. Candidate systems capable of producing this range of power have also been identified and are currently under development. For near-future application the leading contenders are solar-array systems, Rankine cycle turboalternator systems deriving heat from a nuclear reactor source, and Brayton cycle turboalternator systems deriving heat from a nuclear reactor or radioisotope source. While each of these systems has individual application problems and unique advantages, disadvantages, and constraints, inherent features common to all power systems must be considered in the design of the control-logic system.

To date work has been done in the area of speed control through the use of variable alternator loading (refs. 1 and 2). However, these systems utilize the alternator (ac) output directly, which means the loads may have to operate at frequencies as high as 1200 Hz.

The Manned Orbital Research Laboratory studies (MORL) of reference 3 indicate that a dc system may be preferable to an ac system for spacecraft. The conclusions of this study show that an electrical power system should be sized for average power requirements and that variations should be furnished and absorbed by an energy-storage device. Such a system was designed and built as a combined project of the Langley Research Center and Manned Spacecraft Center (ref. 4). A breadboard load logic and control system simulating partial spacecraft loads was integrated with the Brayton Cycle

Demonstrator. Parasitic loading, mandatory real loading, permissive real loading, and conditioning equipment were integrated into the control method, and distribution and load priority considerations were included.

The system described in reference 4 uses the rotational speed of the alternator as the main control input to the load and power management computer. Such a control philosophy requires that all load transients generated in the system be reflected through the alternator and measured as speed changes. Thus the response of the system is greatly influenced by the rotating mass of the alternator. The combination of time delays inherent in such a system makes stability difficult to achieve, and system response to perturbations is slow.

The system described in the present paper eliminates the single major source of time lag. The system control input is no longer the alternator speed, but rather the alternator terminal voltage, which is more sensitive to changes in load level. This approach eliminates a large portion of the power conditioning equipment necessary in the original approach, while improving the system response characteristics.

OPERATIONAL CONCEPT

The general design of any spacecraft power conditioning system must include the subsystems in figure 1. In practice, other subsystems may also be necessary. When the power source is a Brayton or Rankine turboalternator, the full generated electric

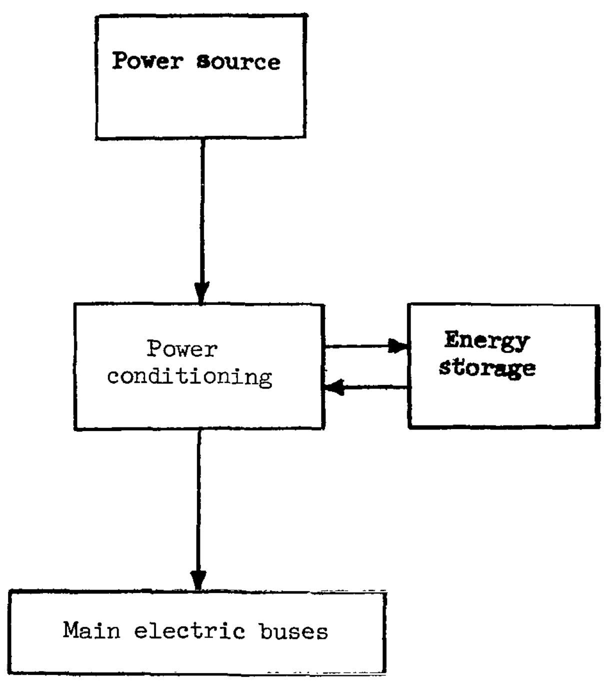

Figure 1.- Basic load-control and conditioning system.

power must be consumed at all times in order to prevent the rotating unit from exceeding its design speed. Thus, such a system will require a parasitic load that absorbs excess energy when electric usage is below the output capability of the source and full use has been made of the energy-storage device.

Figure 2 shows a block diagram of the system that was designed specifically for a Brayton or Rankine power source. The system can, however, be readily modified for other power sources. The full output power of the turboalternator is rectified to form a dc bus. This voltage is then applied directly across the battery, parasitic load, and any

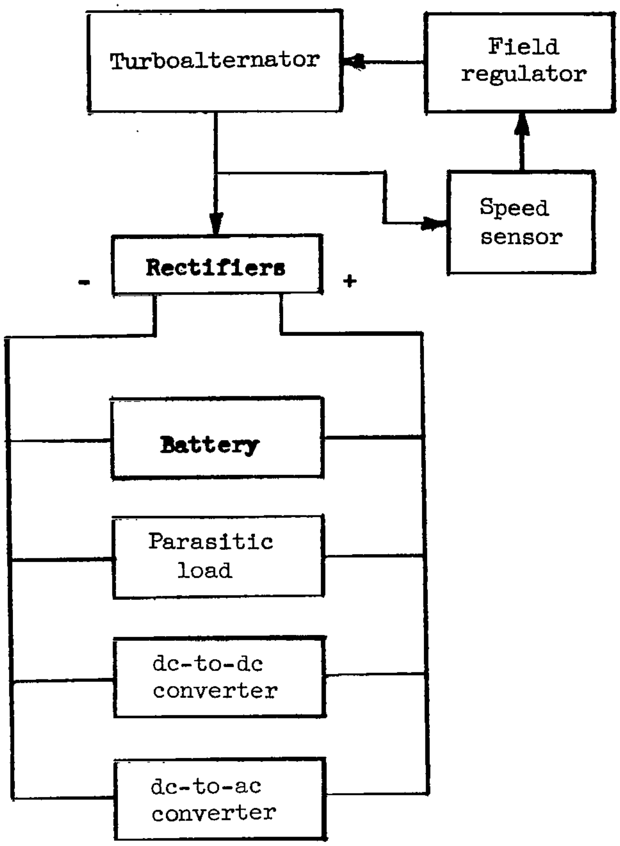

Figure 2.- Voltage-controlled load and conditioning system.

inverters and convertors that may be required. As a minor control loop, the alternator speed is sensed and used to control the field regulator. The field regulator then varies the alternator field current to adjust output power and thus speed.

Since the output of the alternator is likely to be high voltage (100 volts or more), direct rectification will result in high-voltage dc buses. These buses provide certain advantages: (a) a convenient tie point if two or more alternators are to be operated in parallel and (b) a voltage level suitable for high-power transmission over longer distances.

It may be desirable to have filters on the output of the rectifiers (choke input) to reduce the rms current to its dc value. This addition can reduce the alternator internal losses and potentially improve efficiency. Because dc grounds are not required in this system, shock hazards are minimized, and single-order shorts to ground will not cause a loss of power. The alternator neutral is likewise not required, and thus the problems of single-point failures are further reduced.

Energy storage in this system is provided by nickel-cadmium batteries. This selection was made on the basis of cost and immediate availability. Other candidates for a flight system are reverse-cycle fuel cells or any efficient battery. The test system was designed for a 90-volt dc bus, again because of the availability of the energy-storage elements.

The parasitic load consists of a bank of power resistors driven by an active circuit that is placed directly across the bus, and its action is similar to that of a large zener diode. It functions to limit the bus voltage from rising above the end-of-charge voltage of the battery. The parasitic load will then draw whatever current is necessary to limit the bus voltage to this value. This scheme allows the battery to charge or fully support the high-voltage bus with no additional power-conditioning equipment or logic circuitry for either function. Using the natural characteristics of the battery and parasitic load in this manner does allow the bus voltage to fluctuate with load. This feature should not be detrimental to the low-voltage dc or the inverter-supplied ac buses. Inverters and converters can be designed to yield regulated output when the input varies over a moderate range. The dc-to-dc converter designed for use in the investigation of reference 4 operated satisfactorily with input voltage variations between 90 and 150 volts dc. The need to design for a variable input voltage sacrifices very little in efficiency. In general, however, the higher the input voltage, the more efficient the conversion process.

The main dc converter and the ac inverter were not supplied in this demonstrator system. Equivalent loading was simulated through the use of switched resistance.

Two alternator parameters are sensed and used as system controls. They are the rotational speed and the terminal voltage. The speed sensor can be of a simple linear type and is used to control the field voltage. An increase in speed produces an increase in field, and thus more power is generated and the alternator tends to slow down; and conversely for a decrease in speed. The terminal voltage, after rectification, is applied directly across the battery. Also connected across the battery is the parasitic load. When the battery voltage exceeds a preset value, the parasitic load begins to conduct current, simulating the action of a large zener diode. Thus, the battery voltage is prevented from rising above its end-of-charge voltage. In this manner each parameter is independently controlled. Cross-coupling of control loops is kept to a minimum and system instability is prevented.

THEORY OF OPERATION

The operation of this system is analogous to that of a rechargeable battery in parallel with a zener diode and an input that is constant in power; that is, a reduction in voltage results in an increase in current from the source so that the product of voltage and current is always constant. The loading is then simply resistive across the battery. The schematic diagram of figure 3 shows this simplified model.

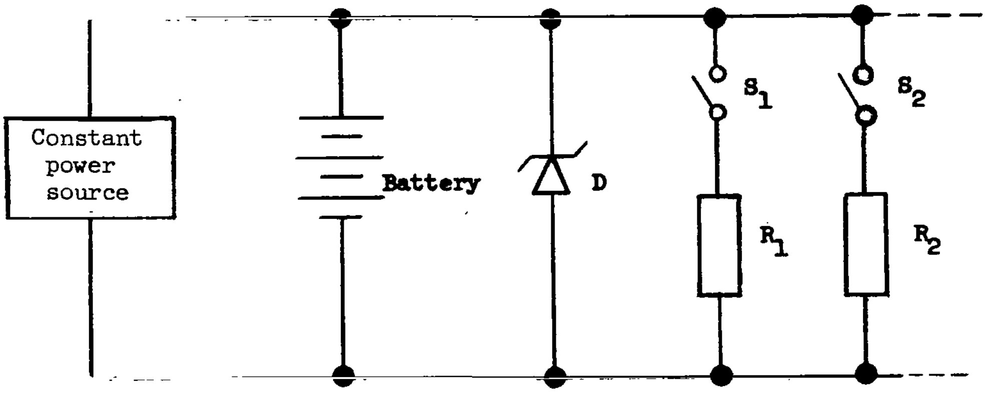

Figure 3.- Control-system equivalent circuit.

The battery consists of a pair of 45-volt nickel-cadmium wet cell batteries connected in series to establish a 90-volt bus. Figure 4 is a typical curve of the relation between the nickel-cadmium cell voltage and state of charge. As charge is increased there is an extensive plateau at about 1.4 volts. At a charge of approximately 85 percent a "knee" is observed where the voltage rises to another plateau of about 1.6 volts. The

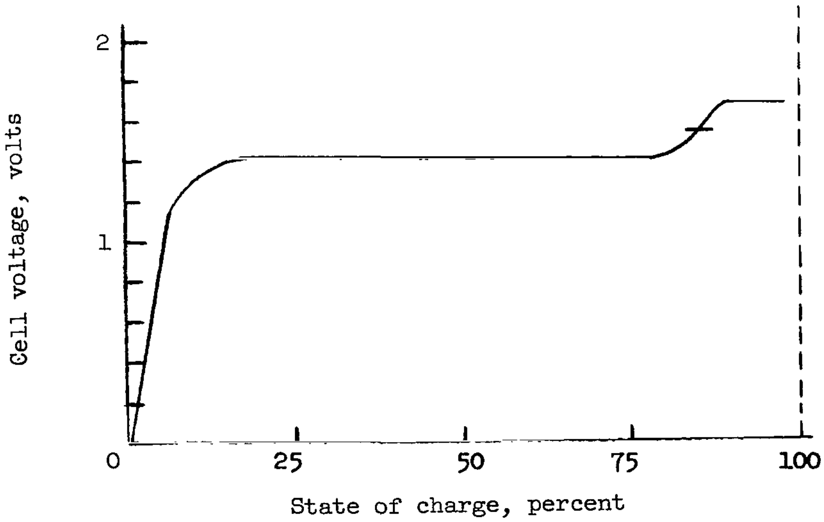

Figure 4.- Charge characteristics of nickel-cadmium battery.

100-percent charge is assumed to be on the second plateau. However, the higher voltage region results in inefficient charging because of increased heat generation and excessive outgassing of the cells. In order to eliminate this type of problem, the maximum cell voltage was limited to 1.47 volts, which is about halfway up the knee. In this range of charge the battery is reasonably efficient (approximately 85 percent), and no problem exists with outgassing or heat.

The zener diode labeled D in figure 3 is a symbolic representation of the parasitic load. The conduction voltage was adjustable and was set at 90 volts. Figure 5 shows the relation between current and voltage of this parasitic load.

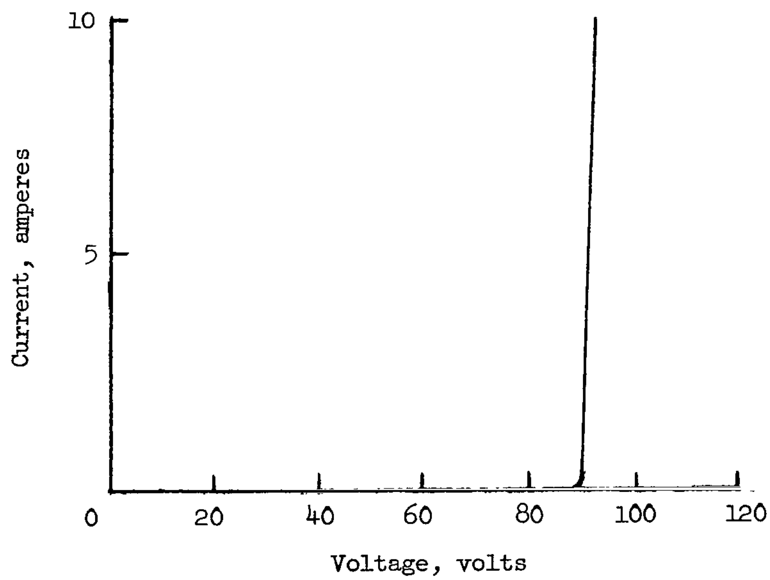

Figure 5.- Relation between current and voltage of parasitic load.

The resistors R_1 and R_2 in figure 3 are representative of the real or useful loads which are switched in and out. As the system is started, the power source is turned on and the energy is absorbed by the battery. After the battery becomes charged, the bus voltage rises to 90 volts. When this point is reached, the parasitic load D begins to conduct, preventing the voltage from rising further. The battery current then decreases and finally reaches some trickle-charge value which is quite low – less than 0.5 ampere in this system. The system is now in a state where the parasitic load is absorbing nearly all the power generated by the source. If S_1 is closed, current will flow through R_1, which represents a load of 50 percent. In order to equalize the system, the parasitic load will decrease its conduction current by an amount equal to the current drawn by R_1. The bus voltage has not yet varied more than 0.5 volt. The battery is still fully charged and consuming a trickle charge. The system load is being satisfied by the source, and the extra energy is being absorbed by the parasitic load. If S_2 is also closed, current will flow through R_2. If R_2 has been sized to draw approximately the full load (100 percent of power-source energy), then the combination of R_1 and R_2 presents an overload. In order to satisfy the current through R_1 and R_2, the parasitic load will turn fully off. This, however, is not enough, and the bus voltage will start to drop. Because of its natural characteristics, the battery will supply current to the external circuit when the terminal voltage is reduced. In this condition the system is using about 150 percent of full load capacity; the power source is providing 100 percent and the battery the remaining energy. This condition can continue until the extra load is dropped or the battery discharges to its set limit. If S_2 is opened after a period of time, the load demanded by the "real load" returns again to 50 percent and the excess energy from the power source will be absorbed by the battery. The battery will accept this excess until its terminal voltage again returns to 90 volts. When this happens the battery is nearly fully charged, and the parasitic load will begin to draw current to prevent the voltage from rising further. The battery current will then slowly reduce to a trickle charge and the system is fully recovered.

The important thing to note is that at no time will the source be called upon to provide more than its steady-state energy. Thus, the source has not experienced any power transients. The only effect that has been transmitted back to the source is a small and relatively slow variation in terminal voltage. If the reduced terminal voltage results in speed variations, the speed sensor will control the field voltage through the field regulator and maintain correct speed and a fixed output power. Since the source terminal voltage has varied only slightly, small corrections in field voltages are all that are required to maintain speed, and no large or rapid transients are noted in alternator speed. It is this feature that is so important when system stability is considered.

In the design of this demonstrator system several areas were purposely omitted. The protective, monitoring, and priority logic circuitry necessary for mission control and reliability were not studied in depth, nor was specific conditioning equipment. Such problems as exist in these areas are common to all control philosophies. Protective circuits, however, become simpler because of the large fault-clearing capacity of the battery, which is unhampered by the current limitations of power-conditioning circuitry.

RESULTS AND DISCUSSION

The system described was built and tested with a simulated Brayton cycle turboalternator. The simulator consisted of a 24-volt automotive-type alternator driven with a separately excited dc motor. The motor supplied a nearly constant torque to the alternator. This is a close approximation to the combined rotating unit that is typical of a Brayton cycle machine operated with a very small speed deviation about its maximum power point.

Figure 6 shows a portion of a recording of one test run. The operating power level from the alternator in this run was about 450 watts with a peak real load requirement of 970 watts, more than a 100-percent overload. There were no transients or perturbations in the alternator output current; there was some variation with bus voltage and "noise" which was traced to brush arcing in the driver motor. Load switching was not visible in the output of the alternator. In this simulation the maximum bus voltage was 90 volts. One minute after a 115-percent overload the bus voltage had dropped to 78 volts, or nearly 15 percent below maximum. The parasitic load is observed to be operating in the manner predicted; it draws current only after the battery has been charged and the bus voltage has risen to 90 volts. The parasitic load then draws only enough current to hold the voltage at this level, and the battery current remains at a low trickle-charge level. It should be noted that these tests were conducted with wet cell nickel-cadmium batteries. For spacecraft, sealed cell batteries would be used and the voltage variations on the bus would be greatly reduced.

Variations of alternator speed could not be detected with the installed sensor and so were not included in these recordings. Thus, a very simple speed sensor is adequate for this type of system.

The battery current can be seen to absorb any load-switching transients when the total load demand is in excess of alternator output power or during the battery charge mode.

The tests represent an unusually severe case of power switching. In any actual spacecraft, the relative load changes would be much smaller. Power changes of less than 1000 watts may be quite frequent, but in a 100-kW system they amount to only 1 percent of the connected load and would not be visible on these recordings.

With the system described here, up to two-thirds of the power conditioners used in the system of reference 4 can be eliminated. Figure 7 shows block diagrams of the two systems. The biggest single difference in system complexity is the elimination of the battery charge and discharge converters. This, combined with the simpler control logic, yields a system which is lighter, simpler, more efficient, and inherently more stable.

CONCLUDING REMARKS

A system was developed that fully controlled the rotational speed of a Brayton cycle turboalternator while providing useful electrical energy. The system is simpler and inherently more efficient than those resulting from earlier efforts. A single parasitic load and battery provide a controlled bus for distribution. From this principal bus, converters can be connected in each module and the resulting interchangeability of equipment between modules minimizes spares and enhances reliability. The advantage of having

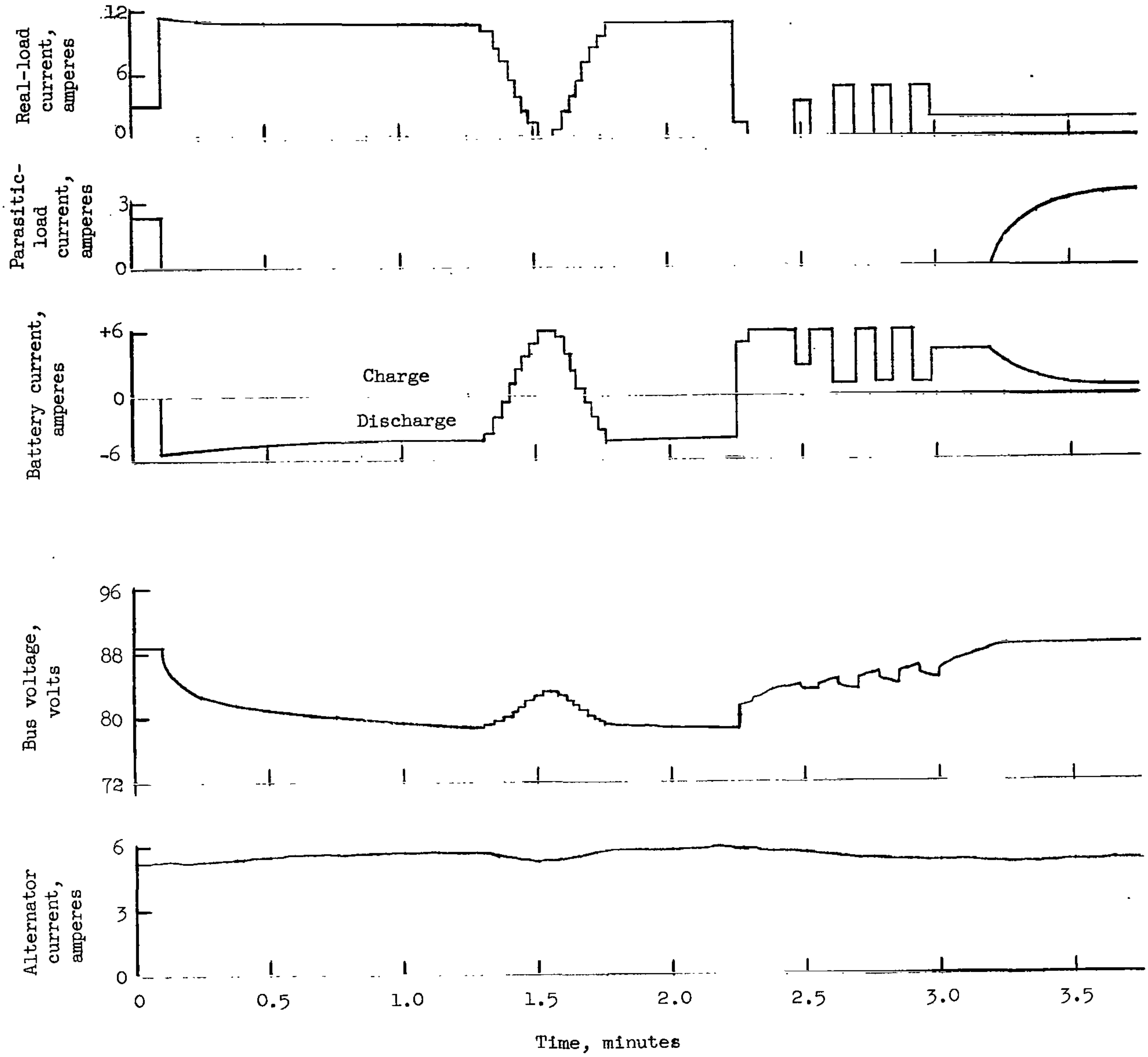

Figure 6.- Control-system test run.

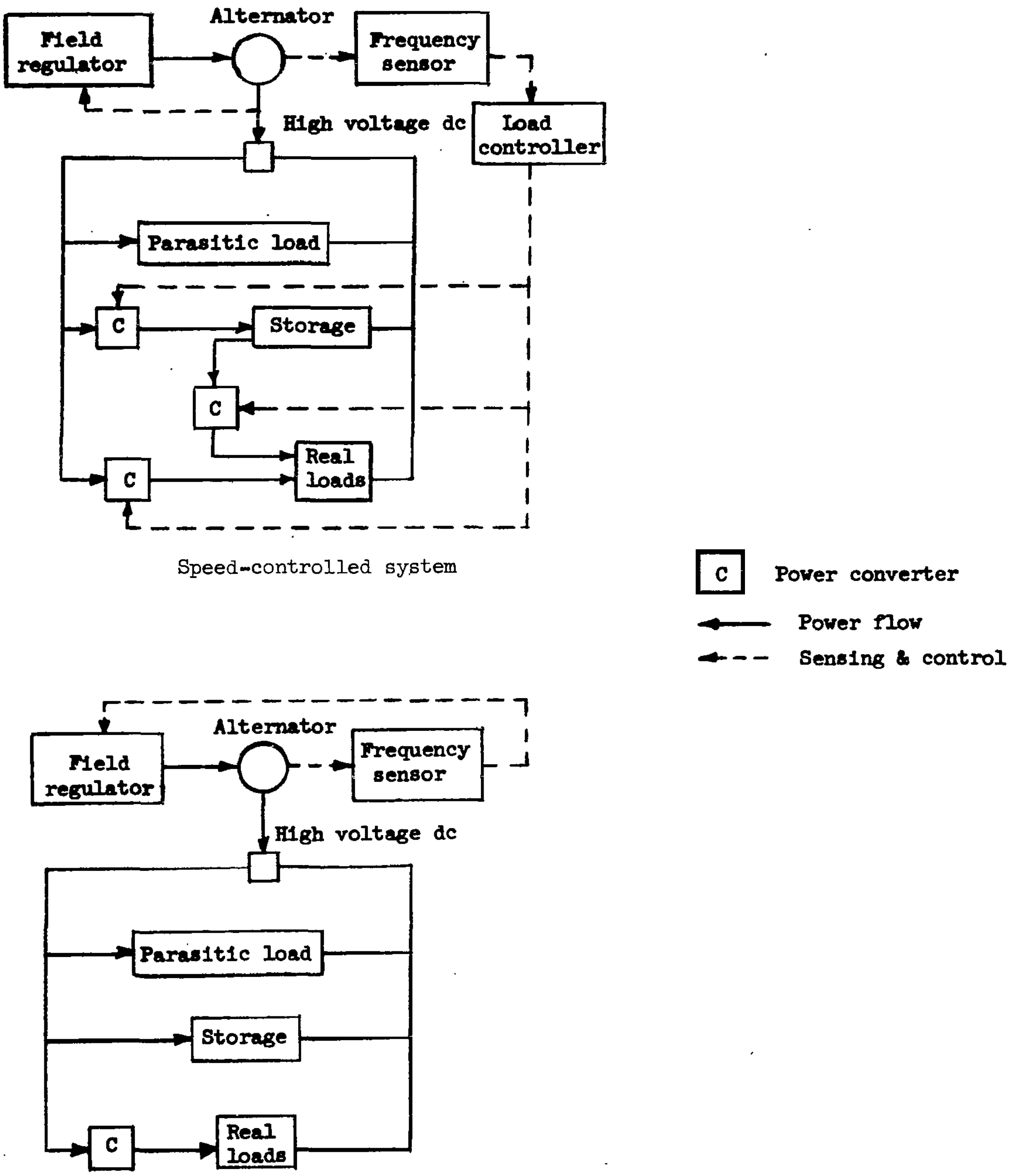

Figure 7.- Comparison of Brayton control concepts.

several small converters delivering practical currents rather than one huge converter is obvious. A dc-to-dc converter in the 1000-ampere range is not off-the-shelf equipment.

The variation allowed in the high-voltage dc bus need not be an objectionable characteristic. Compared to the system in reference 4, this concept provides the same control in a more exacting manner with far less equipment. It offers better system response with increased efficiency and reliability, and does so without perturbations of alternator speed and power.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., December 3, 1971.

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